

Hubble Space Telescope Servicing Mission Four (HST SM4) Unique Challenges for STS-125

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Abstract

The Hubble Space Telescope (HST) has nominally been serviced every three years; but seven years have now passed since the last servicing mission. The current mission (SM4) is much broader in scope than any before, demanding a much higher degree of safety participation in hardware design and mission operations. Unprecedented hardware installation includes batteries, a new science instrument computer and a Soft Capture Mechanism (a structure enabling the future safe de-orbit of HST). The mission includes challenging extra-vehicular activities (EVAs) to restore two instruments never designed for on-orbit repair. Following a successful five EVA day mission, a restored HST should return science well into the next decade and enable a safe de-orbit at the end of observatory life.

Introduction

HST Servicing Mission 4 (SM4) was originally scheduled to launch in October of 2008. However an on-orbit failure inside the Science Instrument Control and Data Handling (SI C&DH) unit caused a slip into 2009. This event is one of a number that have made mission success and safety engineering problematic for the flight on STS-125. As more hardware elements and EVA tasks have been added, operational assumptions and engineering have been revisited leading to both a more effective and safer mission design. New instruments and guidance sensor replacement have been performed before. However in-situ replacement of circuit boards, planned for this mission, has never before been accomplished on-orbit. Along with SI C&DH replacement, emplacement of a Soft Capture Mechanism (for future HST de-orbit), replacement of aging batteries, and repair of on-orbit instruments led to new processes and tools. The new tools and techniques required careful safety assessments, documentation and acceptance to insure a successful mission.

HST Servicing Mission 4 Tasks

With more than 19 years of world recognized science already accomplished, Hubble will be reborn with Servicing Mission 4 (SM4), scheduled for 2009. Astronauts will use the Shuttle to enhance Hubble's capabilities by large factors through new technology by installing modern science instruments, as well as new gyros, batteries and other critical devices to assure continued success through the year 2014. Table 1 lists the tasks and impacts of major EVA tasks associated with HST SM4.

Table 1 - HST SM4 Tasks

Task	Impact to Hubble
Install WFC3 - Wide Field Camera 3	Install a high-resolution/wide-field camera with continuous coverage of wavelengths or colors of light from the ultraviolet to the near-infrared.
Install COS - Cosmic Origins Spectrograph	Install the most sensitive ultraviolet spectrograph ever to fly on HST.
Repair STIS	Restore the Space Telescope Imaging Spectrograph to operational status by replacing circuit boards.
Repair ACS	Restore critical scientific functionality to the Advanced Camera for Surveys by replacing power supply and circuit boards.
Replace Rate Sensor Units (gyroscopes)	Complete change-out of all six gyroscopes, the heart of HST's pointing system, and HST's main wear-out items.
FGS - Fine Guidance Sensor	Last in a series of changed-out units that allow fine pointing of HST.
Replace Batteries	Replace the six batteries originally launched with Hubble in 1990, which are steadily losing capacity as they age.
Install Soft Capture and Rendezvous System	Install the Soft Capture and Rendezvous System on the bottom of Hubble to enable NASA to pursue options for the safe disposal of Hubble.
Install New Outer Blanket Layers (NOBLs)	Install NOBL covers to thermally protect the exterior blankets and maintain normal operating temperatures of Hubble's electronic equipment.
Replace Science Instrument Control & Data Handler (SIC&DH) unit	Replace the original unit launched with Hubble in 1990 to insure redundancy of operations after September 2008 failure of Side A Control Unit/Science Data Formatter (CU/SDF).

HST SM4 Space Support Systems

The HST Flight Support System (FSS) was used on all previous servicing missions and will be used again for SM4. FSS provides mechanical and electrical interfaces between HST and the Orbiter for payload retrieval and on-orbit servicing. The FSS SM4 configuration provides the following services: HST berthing and positioning; HST latching and release (remotely operated); Orbiter and HST electrical power interfaces; HST optional reboost (structural configuration). Figure 1 shows the Space Support Equipment (SSE) or carriers and some of the hardware complement to be launched in support of SM4.

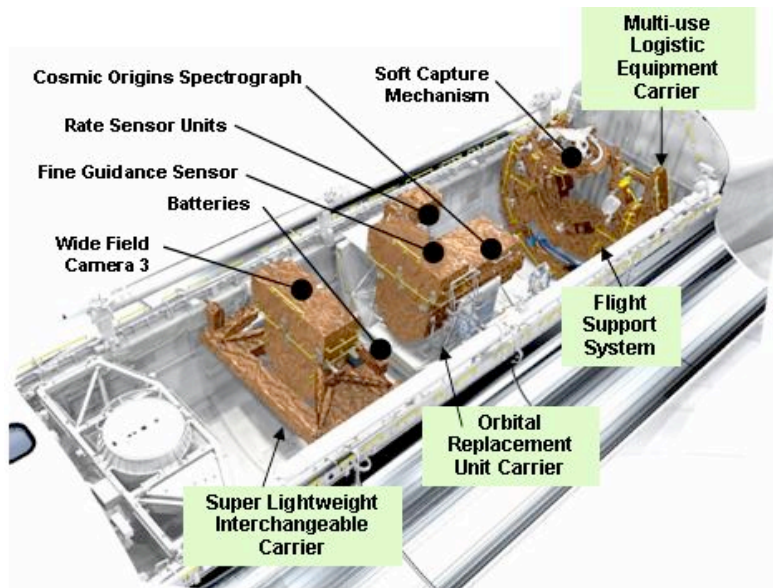


Figure 1 - SM4 Carrier and Orbital Replacement Unit Complement

The Orbital Replacement Unit Carrier (ORUC), another reusable structure, provides stowage and environmental protection for the SIs and ORUs during an HST Servicing Mission. The ORUC structure supports a complement of SSE hardware and assorted crew aids and tools required for HST On-orbit Replacement Unit (ORU) servicing and change out functions. Its approximate launch weight is 7600 lbs. Stowage on the ORUC provides for carrying to orbit HST ORUs, and tools and for returning the replaced units and tools in suitable transport containers. The FSS supplies power and electrical interfaces for the ORUC via a mission unique harness from Shuttle inventory. Electrical circuits are limited to thermal control and monitoring, and status of SI latches in the science instrument protective enclosures

The Super Lightweight Interchangeable Carrier (SLIC) is new for SM4 and offers a lightweight alternative for the HST Servicing Mission 4 manifest. With its composite construction, this carrier departs from the traditional aluminum carrier structure both in terms of its weight and its expected performance. Like the ORUC, SLIC carries ORUs and tools and provides power and monitor capabilities using Orbiter power.

The Multi-Use Logistic Equipment Carrier (MULE) structure consists of hardware that was previously flown on several missions including: STS-109 as part of the HST SM3B mission ; STS-95 as part of the HOST mission that was launched on October 29, 1998; and STS-48 as part of the Upper Atmospheric Research Satellite (UARS) Observatory mission that was launched on September 12, 1991. The UARS hardware, which was re-flown for the HOST mission and HST SM3B mission, will now be implemented for the HST SM4 mission once again as the MULE. MULE carries ORUs (notably the SIC&DH replacement) and tools. MULE also provides a structural platform for the Relative Navigation System (RNS), an experimental platform for developing automated rendezvous techniques. As for the ORUC and SLIC, MULE provides power for heaters and monitors.

Reflown Hardware and Safety Heritage

Approximately half of the hardware flown for SM4 is considered heritage hardware or “Reflown” hardware. This includes the structural, mechanical, and electromechanical systems on all four carriers as described above. Other Reflown items are related to HST operations and re-use of crew aids and tools (CATS) from previous missions. While the reflown assessment process was employed for documentation purposes, all hazards were revisited with the same rigor that is afforded any new payload hardware. SM4 reflight assessment has thus been completed twice; once before the Columbia accident and most recently after reinstatement of the mission.

Reflight assessments include identifying all reflown hardware and ground support equipment, determining the safety of each item, and developing new or revised Hazard Reports (HR), including the identification of HRs no longer applicable, and to the safety impact of hardware/software operations. Reflight assessments also include a copy of the baseline phase III HRs, requisite re-verification activities, identification of new verifications, assessment of all non-compliant and limited life items, details of maintenance/inspections, description of previous testing and ground/flight anomalies, and corrective action for continued use.

HST SI C&DH Failure and Impacts

The Science Instrument Control and Data Handling (SIC&DH) provides a command and data interface for all HST Science Instruments, the NICMOS cooling system, and the Data Management Subsystem. In September 2008, the on-orbit SIC&DH failed on Side A. HST had operated on Side A of the SIC&DH since its activation on-orbit in 1990. An investigation concluded that the Side A failure was a hardware failure related to the Central Unit Science Data Formatter (CU/SDF).

Once the operations team determined that the SI C&DH A side failure was hardware related, the decision was made to delay the mission to allow further evaluation of the failure and to provide for the addition of a spare SIC&DH to the manifest. A spare unit was built at around the same time HST was originally launched, however the condition of the unit was unknown at the time this decision was made. The operations team eventually determined that the loss of the SIC&DH A side reduced the potential lifetime for HST significantly. Thus, in order to insure the continued successful production of science data into the future, the decision was made to add the replacement SIC&DH (SIC&DH-R) to the manifest.

Initially, the delay was to be until February 2009. However, the condition of the spare unit was identified as a key risk since it was determined that full flight certification was not completed during the initial build. Built in 1991, most of the unit had been safely in storage. However, some of the boxes had been removed to facilitate testing of other ORU's and instruments. The spare was reassembled, and certified via flight acceptance testing (the individual boxes had been environmentally tested for flight).

While the SIC&DH-R was being reassembled and tested, assessment of the EVA task was begun by conducting analysis and by rehearsing the installation in the Neutral Buoyancy Lab (NBL). During testing and analysis, several differences were found between the on-orbit unit and the spare unit. A key difference was that the spare unit requires slightly more power and produces more heat than the on-orbit unit. The analyses included a careful look at each task and each aspect that could affect the successful installation. A major issue identified during the task assessment was that a significant thermal mismatch could occur during change-out for both the on-orbit unit and its replacement. Mitigating the thermal distortion effects required several redesigns of the interfaces as well as the EVA installation process to insure a successful on-orbit change-out. A key issue for Safety was to insure that the new materials, interface redesign and selection of bolt-order did not adversely affect on-orbit safety or the ability to safely land the Orbiter with either unit installed.

Having already provided for a full compliment of instruments and tools before the SIC&DH-R was added to the manifest, selecting an EVA accessible location which also provided heat and the ability to provide flexible interfaces was the next challenge. Fortunately, a location on the MULE carrier had been reserved in the event a spare reaction wheel was added. This was chosen for stowage of the SIC&DH. The SIC&DH Plate Assembly (SPA) was designed to provide the same interface for the SIC&DH as found on HST. The SPA design underwent several iterations to accommodate not only the expected thermal mismatch, but also the mechanism fault tolerance requirements enforced by Johnson Space Center's Mechanical Safety Working Group (MSWG). Additionally, the SIC&DH-R required modifications to its fasteners to compensate for the thermal distortion as the problem is expected to be worse on installation to HST. Figure 2 shows the SI C&DH being mounted for flight to the MULE.



Figure 2 – SI C&DH Being Installed at KSC Prior to Flight

Other major risks for the SI C&DH change-out include the potential for exceeding allowable kick loads and high Portable Foot Restraint (PFR) socket loads. Analyses determine whether or not the structure can sustain kick loads without producing a sharp edge (failure to ultimate). This analysis is performed for all payload items and then communicated to the crew via the HST EVA Contact Restrictions Document's kick load maps. Each PFR must be evaluated for capacity as the crew has at its disposal a variety of extenders which can affect the ability of the substrate to carry the load. This evaluation is completed by first having the crew perform the change-out in NBL, then taking the equipment used in the sockets used and calculating what combination of PFR and PFR extenders are allowable. This analysis is completed to prevent damage to the Space Support Equipment and to HST. With the late

addition of SIC&DH, this evaluation was accelerated, due to the fact that part of the evaluation could not be completed until the stowage location was determined.

Soft Capture Mechanism Addition

When launched in 1990, HST was to return to earth on a Shuttle. However, changes in safety requirements and shuttle weight limitations nullified this solution to a safe de-orbit of Hubble. Additionally, the last shuttle will complete its final mission in 2010 and all flights after SM4 are designated for International Space Station logistics. The Soft Capture Mechanism (SCM) was thus conceived to enable automated capture and safe de-orbit of HST.

HST's aft bulkhead was designed to be flexible, allowing for expansion and contraction due to normal thermal fluctuations, however automated rendezvous and capture requires a stable platform. Thus, the SCM must provide a stable platform for rendezvous and capture without impacting science data production. Three berthing pins on the aft bulkhead are used to secure HST to the FSS during shuttle servicing. These same three berthing pins were also selected as the mounting points for the SCM due to their stability and location. Thus, the SCM must be installed on-orbit to the same fixtures being used to constrain HST to the FSS and thereby the Orbiter.

SCM thus poses multiple safety hazards. It must launch on the FSS, fit between the FSS and HST on-orbit and be safely installed by the crew in a minimum amount of time. Additionally, the SCM must either be sufficiently connected to HST for a safe deploy or remain connected to the FSS for a safe landing. Otherwise, there is a risk that the SCM could prevent HST from being correctly deployed (HST connected to FSS via SCM) which would be catastrophic since the FSS cannot be jettisoned with HST.

From the very beginning, HST's safety team followed the SCM design, performing an initiating event tree analysis (IETA) for each design iteration. HST's safety team became an integral member of the design team and influenced the design to insure that each major function includes safety features and EVA overrides. Additionally, steps were added into the EVA installation process to insure that the SCM is completely released from the FSS prior to connecting to HST. A contingency flow was constructed and provided to the EVA team to address potential cases identified as safety critical using the IETA. Figure 3 is a photo of the SCM as installed onto the FSS.

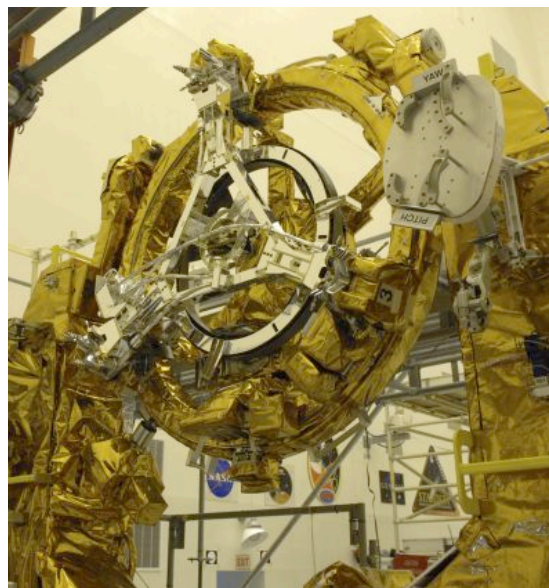


Figure 3 – SCM Shown on FSS

The following safety features were incorporated into the SCM design: Indicator lights and microswitches to insure that the crew can determine whether or not the remote drive functions properly; a mechanism to insure that the gearbox cannot inadvertently release or deploy the SCM attach or release mechanisms; overrides for attachment to FSS and HST; and overrides for release from HST and FSS

A major issue for SCM during the IETA was making the distinction between Mission Success and Safety. Since the SCM is to attach to HST, it must be designed so that, once installed, it does not interfere with HST's Pointing Control System (PCS). However, from a safety standpoint, SCM must simply either be detached from the FSS and sufficiently attached to HST so that, upon deployment, it flies with HST, or be safely attached to the FSS for landing. The IETA helped drive out these issues and led to clear distinctions between safety-related design issues requiring two-fault tolerance and mission success issues requiring single-fault tolerance. Figure 4 shows the final fault-tolerance flow diagram with the various paths for safety and mission success.

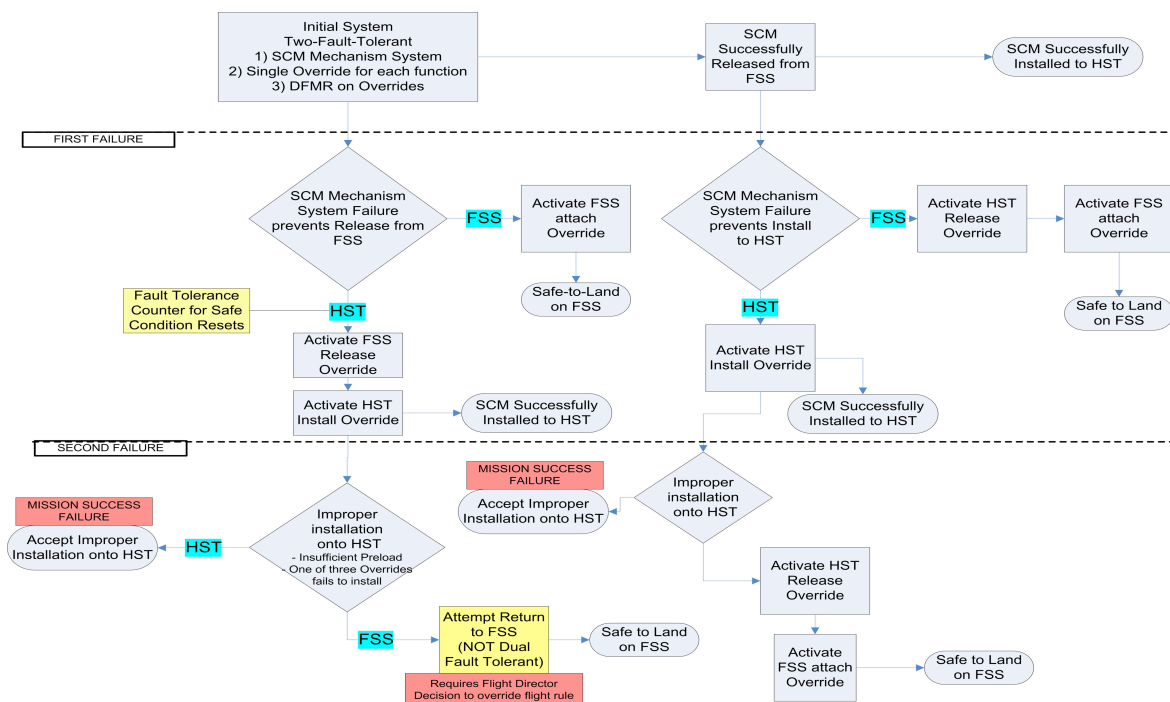


Figure 4 – Fault Tolerance Flow SM Safety and Mission Success

Nickel Hydrogen Battery Replacement

A primary goal of SM4 is to replace HST's 18 year old batteries. HST's batteries are some of the oldest batteries of their kind on orbit as they were part of the original deploy mission in April 1990. Since the deploy mission, shuttle safety concerns have meant imposing stringent requirements on payload batteries. For HST, the new batteries must launch in a charged state, and so the replacement batteries must provide isolation between the battery and the connectors to avoid an ignition source. HST's original battery design did not account for such a device. HST's electrical team chose a Commercial Off The Shelf (COTS) switch designed originally for tank headlights. Shortly thereafter, the HST servicing mission was cancelled in favor of a robotic mission.

When the servicing mission was reinstated, HST's safety team looked carefully at every aspect of the safety features provided for the switch. The team discovered that this switch was designed so that the tank headlights would remain on should the switch fail and thus is not a Fail-Safe design. Additionally, the team discovered that Cadmium plating was applied to the switch to prevent corrosion and also that, should one screw loosen during launch, the handle could come loose.

Cadmium plating has properties similar to Tin and can form whiskers which could cause current to inadvertently flow to the switch. As a result of this discovery, GSFC's Materials Branch examined one of the switches and did discover whiskers. Further analysis showed that such whiskers could not sustain sufficient current to arc or spark.

The lack of back away prevention on the handle fastener of the switch was mitigated as it was discovered that loss of the handle causes the switch to close, energizing the connectors. Barrier analysis was applied to the switch to insure that, no matter what happened internally, the switch could not harm the crew. As a result, backaway prevention was added to the handle fastener and a non-conductive paint was applied to the switch handle. Figure 5 shows one replacement battery and the Battery Isolation Switch.



Figure 5 - HST SM4 Replacement Battery

EVA Operations

STS-125 for SM4 flies a crew of seven for an 11+2 day mission. The mission crew is further subdivided into two EVA crews with which will complete five scheduled EVA days. Each EVA lasts about 6 hours and uses a team of two crewmembers. Resources for one unscheduled EVA are provided to protect for HST servicing problems and deployment day concerns. An additional day provides time for additional tile inspections and repairs if needed.

The development of EVA day operations is an interactive process of engineering, prototype, crew trials, re-design, and training. Activities include Neutral buoyancy Laboratory runs, crew briefing, one-gravity trainer sessions, and virtual reality sessions. All lead to final designs for EVA tools and techniques needed for the given tasks on any EVA day. Safety engineering supports the design process at both JSC and GSFC during development.

The EVA timeline (Figure 6) identifies plans to replace and or repair HST systems. The timeline is carefully crafted for EVA efficiency so as to effectively use every second available for servicing. The first EVA will focus on replacement of Wide Field Camera (WFC) and Scientific Instrument Command and Data Handling module and addition of the Soft Capture Mechanism (SCM) and Latch Over-Center Kits (LOCKs). The second EVA will be used to enhance core HST systems with new rate sensor units (RSUs) and one battery module. EVA 3 tasks include the installation of the Cosmic Origins Spectrograph (COS) and begin repair of the Advanced Camera for Surveys (ACS). EVA 4 time will be used to repair the Space Telescope Imaging Spectrograph (STIS). EVA 5 will mark the final SM4 EVA with the replacement of the Fine Guidance System, completion of the ACS Repair activities, and replacement of the bay 3 battery module.

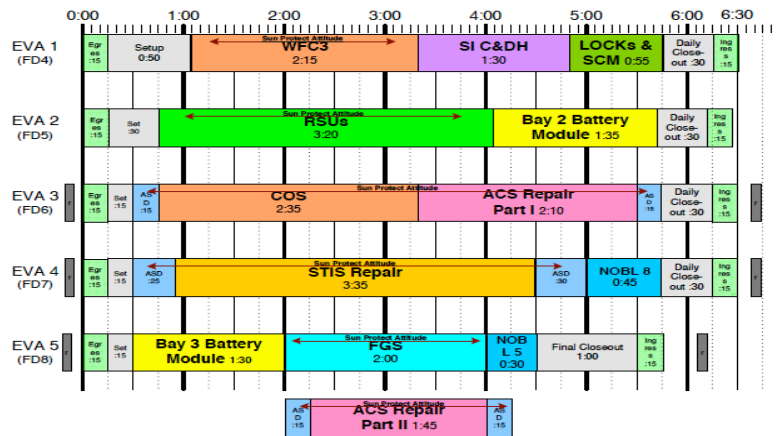


Figure 6 - HST SM4 EVA Timeline

Safety's Role in Designing and Developing Crew Aids and Tools (CATS)

Hubble Space Telescope Servicing Missions challenge the nation's space capabilities by conducting thirty (30) hours of Extra Vehicular Activities (EVA) over five (5) consecutive days. This pushes the crewmembers physically, and presents hazards that must be controlled. HST SM4 includes all hazards present from previous missions along with additional hazards imposed by replacing/repairing science instruments components that were not designed to be changed out on-orbit. To perform these repairs, unique tools had to be developed to permit the precision and complex operations needed to meet these challenges.

HST SM4 tools, called Crew Aids and Tools (CATs), must cut, pry and contain components all the while protecting the crew from exposure to sharp edges or other EVA dangers in order to accomplish the planned tasks safely. To properly eliminate, mitigate or control these new hazards the HST Safety Team worked closely with the CATs Engineers. The CATs design and verification process was well defined and proven on previous missions. This process defined requirements and provided a hardware development process that allowed safety engineers to influence hardware and provide the necessary oversight. The process includes identification of HST and Shuttle Program requirements, hardware development plans, qualification plans, acceptance data packages, and government certification approval reports. Figure 7 outlines the process followed for tool development and certification.

Overall Mission Risks

Overall mission risks for this servicing mission are many and include: shuttle launch, HST payload equipment and servicing operations, micro-meteorite on-orbit debris (MMOD), and a high orbit making it impossible for the crew to seek safe-haven at the ISS. The risks have been mitigated using a variety of approaches including:

Orbiter Inspections: For STS-125 the Orbiter Boom Sensor System (OBSS) is being carried on the starboard side of the Orbiter. This is similar in size to the Remote Manipulator System (RMS). Thermal Protection System (TPS) repair tools and materials, and additional equipment to support Contingency Shuttle Crew Survival (CSCS) operations are being manifested in the crew cabin.

Planned TPS inspection will be performed just after launch. When “focused inspections” (FI) are required (as a result of findings after post ascent inspections), the goal is to minimize EVA impacts and do the FI activities in parallel with EVA preparations. This could impact any or all of the preplanned HST SM4 EVA tasks. Post ascent inspections results may warrant additional inspection activities after HST is berthed on FD3.

HST Risks: As with other Shuttle payloads, HST SM4 completed several safety reviews in parallel with design review activities. Late changes and postponement of launch opportunities resulted in several expedited safety reviews, technical interchange meetings, and a multitude of specialized safety working groups.

Hazards were identified and verified/reverified for HST and carrier component structures, mechanisms, radiation, commanding, materials, radiation sources, batteries, hazardous fluid leakage, rapid safing, rotating equipment, and EVA crew hazards. Hazards which could not be controlled (i.e. do not meet safety requirements) were categorized as risks and received additional scrutiny. Risks brought forward needing program resolution included electrical connector mate/demate (molten metal hazard), EVA kick loads resulting in structural failure, portable foot restraint loads, and crew contact hazards as pertaining to sharp edges and thermal extremes.

Primary control of accepted risk hazards is dependent upon EVA crew cognizance and operational avoidance for kick load and PFR hazards. Relative to touch temperature, hot and cold spots exceeding Extra-vehicular Mobile Unit (EMU) limits were identified and implementation of crew training, glove heaters, and operational controls applied to mitigate the hazards. All hardware flown on SM4 was inspected for sharp edges which were removed when possible. Existing sharp edges on reflown carriers, CATS and on HST are controlled using operational procedures, training, and over-gloves to preclude sharp, pinch point, entrapment, or protrusion hazards.

EVA electrical connector demate/mate risk posture was improved for SM4 by including additional upstream inhibits and reducing the number of hot mate/demates from 137 to 32. Acceptance of the 32 connectors was resolved using multiple techniques to minimize downstream loads and crew training.

Micro-meteorite Orbital Debris (MMOD): Mitigation of the MMOD risk requires the Shuttle attitude timeline be optimized to fly protected attitudes when not conflicting with necessary HST required attitudes. Time is necessary for late MMOD inspection and repair once HST is released by the end of FD9. TPS inspections may also be performed on FD 9 and FD10 to inspect for MMOD damage. Unlike previous missions, only one unscheduled EVA is available and it must support both unfinished SM4 tasks from the past EVAs as well as correct any HST release concerns.

Launch on Need (LON): Another Space Shuttle will be available for a LON rescue mission following the SM4 launch date. KSC will support both STS-125 and STS-400 LON.

NASA has evaluated the risk for SM4 and, with the mitigation above, has characterized it as being in family with that necessary for an International Space Station mission. The largest risk is that associated with MMOD and has been mitigated by flying protect attitudes.

Conclusion

Technical and administrative issues presented unique challenges to flight safety for SM4. Technical issues were addressed by insuring that hardware design included considerations for safety in the earliest phase possible. As the PSRP had not processed an SM4 mission since 2002 and procedures as well as personnel changed in the interim, HST's SM4 team worked closely with the panel to insure all safety requirements were met and that the panel understood both the issues and their solutions. This included pioneering a new process previously used only on for space station payloads. HST's vigilance with regard to including safety in design and in developing and maintaining clear, concise communication with JSC's PSRP will result in a successful SM4.